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HANDLING AND DISPOSAL OF SLUDGES FROM COMBINED SEWER OVERFLOW TREATMENT

Phase I - Characterization

Municipal Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio 45268

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Phase I - Characterization

by

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of the environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, a most vital communications link between the researcher and the user community.

This report discusses the results of a characterization and treatment feasibility test program for the handling and disposal of the residual sludges from combined sewer overflow treatment systems.

Francis T. Mayo, Director
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ABSTRACT

This report summarizes the results of a characterization and treatment test program undertaken to develop optimum means of handling and disposal of residual sludges from combined sewer overflow (CSO) treatment systems. Desk top engineering reviews were also conducted to gather, analyze and evaluate pertinent information relating to pump/bleedback of the treatment residuals to the dry-weather sludge handling/treatment and disposal facilities.

The results indicate that the volumes and characteristics of the residuals produced from CSO treatment vary widely. For the residuals evaluated in this study, the volumes ranged from less than 1% to 6% of the raw volume treated and contained 0.12% to 11% suspended solids. The volatile content of these sludges varied between 25% and 63% with biological treatment residuals showing the highest volatile content and fuel values. The heavy metal and pesticide concentrations of the various sludges were observed to be significant and are presented.

It was concluded that the pump/bleedback of CSO treatment residuals may not be practical for an entire city because of the possibility of hydraulic and/or solids overloading of the dry-weather treatment facilities and other adverse effects. However, controlled pump/bleedback on a selective basis may be feasible. For low solids content residuals (storage, screen backwash, waste activated sludge, etc.), gravity or flotation thickening were concluded to be the optimum steps for the removal of the major water portion while centrifugation and vacuum filtration were concluded to be the optimum dewatering techniques for the high solids content residuals (settled storage treatment sludge, flotation scum and other thickened sludges) prior to their ultimate disposal by incineration or landfill. As a result of the findings and conclusions of this initial study, the USEPA is now involved in a followup study to:

1. Evaluate on a pilot scale basis the process treatment systems of thickening followed by centrifugation or vacuum filtration for handling and disposing of CSO treatment sludges, as well as stabilization methods such as anaerobic digestion.
2. Develop capital and operating costs for the above mentioned treatment systems.
3. Evaluate alternative methods for ultimate disposal of storm generated residuals and assess the potential impacts of such handling and disposal.

This report covers a period from March, 1973 to February, 1975 and was submitted in partial fulfillment of Contract No. 68-03-0242 by the Environmental Sciences Division of Envirex Inc., under the sponsorship of the U.S. Environmental Protection Agency.

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This investigation was carried out by the Environmental Sciences Division of Envirex Inc. Many people contributed to the success and timely completion of this project. Messrs. Richard Wullschleger, Ernest Bollinger and Mahendra Gupta participated in the bench scale treatment feasibility work. The laboratory analyses were conducted by various personnel of Envirex's process laboratory under the supervision of Richard Wullschleger. The evaluation of the collected data was conducted by a team of engineering personnel led by Mahendra Gupta, Project Manager, and Anthony Geinopolos, Project Director. Other members of the engineering evaluation team were Steve Vanderah, Ernest Bollinger, Charles Hansen, and Michael Clark.

The various CSO treatment facilities operators, engineers, supervisors, contractors, administrators and regional EPA officers were most helpful in providing the sludge samples, past data and other necessary information throughout the conduct of this study. It is impossible to mention all those who have contributed to the success of this project. However, special mention must be made for the support of the project by the U.S. Environmental Protection Agency and the willing assistance and helpful advice of the Project Officer, Mr. Anthony Tafuri and Mr. Richard Field, Chief, Storm and Combined Sewer Section, EPA, Edison, New Jersey.

SECTION I

FINDINGS AND CONCLUSIONS

1. Raw CSO Sludge Characteristics

   a. The sludge volumes produced from the treatment of combined sewer overflows varied from less than 1% to 6% of the raw flow volume treated.

   b. The solids concentration of the sludge residuals from CSO treatment varied widely, ranging from 0.12% to 11% total suspended solids. The wide range observed is attributed to the CSO treatment method used and treatment plant operation.

   c. The volatile content of the sludge solids varied between 25% and 63% for the sludges obtained from the treatment types investigated. Biological treatment sludges showed the highest volatile solids fraction (about 60%), whereas that for sludges from physical/chemical treatment showed only 25% to 40% volatile fraction.

   d. As might be expected, the biological sludges with higher volatile solids also showed higher fuel values compared to other sludge types. The average fuel value of biological sludges was 3515 cal/gm (6334 BTU/lb) compared to an average of 2032 cal/gm (3662 BTU/lb) for other sludges.

   e. Pesticide and PCB concentrations in the residual sludges investigated were observed to be significant. Generally, the PCB concentrations were higher than those for pp'DDD, pp'DDT and dieldrin. The Cottage Farm (Cambridge, MA) storage treatment sludge generally showed the higher pesticide concentrations in this study. The range of PCB and pesticide values for the various sites investigated were:

PCB	non-detectable to	6570 µg/kg dry solids
pp'DDD	non-detectable to	225 µg/kg dry solids
pp'DDT	non-detectable to	170 µg/kg dry solids
Dieldrin	non-detectable to	192 µg/kg dry solids

   f. Heavy metal (Zn, Pb, Cr, Cu, Hg, and Ni) concentrations in the residual sludges were also significant, and varied widely for the sludges investigated. Cambridge, MA sludge again showed generally higher heavy metal concentration of the sludges investigated. The range of heavy metal concentrations for the various sites investigated were:

Zinc	697-7154	mg/kg dry solids
Lead	164-2448	mg/kg dry solids
Copper	200-2454	mg/kg dry solids
Nickel	83- 995	mg/kg dry solids
Chromium	52-2471	mg/kg dry solids
Mercury	0.01-100.5	mg/kg dry solids

2. Disposal of CSO Sludges by Pump/bleedback to Dry-Weather Treatment Facilities

   a. From the results of a desk-top analysis it does not appear practical in the cases studied to pump/bleedback CSO treatment residuals from an entire city's combined sewers to an existing dry-weather treatment facility because of the possibility of exceeding the hydraulic and/or solids handling capacities of such facilities. Addition of sludge handling facilities or controlled pump/bleedback of CSO treatment residuals from a portion of a city's combined sewer area would be possible.

      In some cases on-site treatment of wet-weather flow sludges may be practical, particularly when the dry-weather treatment facilities are at or near design capacity. However, before any one alternate is decided upon, site-specific analysis should be performed.

   b. In the cases studied, pump/bleedback of CSO treatment residuals may produce only marginal hydraulic overloadings (10-20% or less) of the dry-weather treatment capacity when the pump/bleedback is spread over a period of 24 hours or greater.

      However, the solids loadings (assuming complete transport and no solids settling in the sewer), may increase as much as 300%, when the pump/bleedback is spread over a 24 hour period (for treatment residual concentrations greater than 1% solids). The impact of such discharge will be proportionately less when the pump/bleedback is spread over periods greater than 24 hours.

      Tolerable solids loadings may result from the pump/bleedback of such low solids CSO treatment residuals as centrates, supernatants, and filtrates from auxiliary CSO sludge dewatering treatments as gravity or flotation thickening, centrifugation, and vacuum filtration.

   c. Pump/bleedback of the retained contents of storage treatment basins may produce hydraulic and solids overloadings of 100% or higher of the dry-weather treatment facilities when spread over a 24 hour period.

   d. The overload effect of pump/bleedback of CSO treatment residuals may produce shock loads (hydraulic, solids, toxic heavy metal levels, PCB and pesticides, low volatile solids, etc.) which may adversely affect dry-weather treatment operation and performance (primary, secondary and sludge handling and disposal).

e. Any reduction in the treatment efficiency of the dry-weather facilities due to pump/bleedback, although small in terms of concentration, can add significant pollutant load in terms of mass loading on the receiving water body. Furthermore, even assuming no reduction in treatment efficiency, at least some fraction of the pumped-back/bled-back residuals would be discharged to the receiving water as a carryover in the treated effluent. This is a disadvantage of the pump/bleedback concept that must be considered in its evaluation.

3. Dewatering of CSO Treatment Sludges

a. Retained contents of the storage treatment at the end of an overflow must be concentrated via conventional techniques such as sedimentation, prior to further thickening of the residuals. The supernatant may then be either discharged to the receiving waterbody or dry-weather sewage treatment facilities (if permissible hydraulically).

Centrifugation was found to be the optimum dewatering process for the on-site treatment of Milwaukee, WI and Cambridge, MA (storage treatment) sludges, based on performance, area and cost considerations.

b. A combination of gravity thickening and centrifugation provided optimum treatment for most CSO sludges evaluated during this study. This combination was most effective for less concentrated combined screen backwash and flotation scum residuals such as for Racine, WI. For more concentrated residuals, such as for flotation scums at Milwaukee and San Francisco, direct centrifugation and vacuum filtration were effective.

c. Basket type centrifuges were indicated to be better suited for dissolved-air flotation sludges (Racine and San Francisco) and biological treatment residuals (Kenosha and New Providence) because of poor scrollability of these sludges.

d. Vacuum filtration in combination with gravity or flotation thickening provided optimum dewatering performance for alum treated dissolved-air flotation (San Francisco) sludge and the biological sludges. However, based on area and cost requirements, the results of gravity or flotation thickening plus centrifugation were comparable to vacuum filtration.

e. No significant differences in dewatering characteristics were apparent for the wet and dry-weather sludge samples obtained from the primary and secondary clarifiers at New Providence, NJ, although the raw sludge residuals were significantly different inherently.

4. Considerations for Ultimate Disposal by Incineration

   a. As previously stated, the fuel values obtained for the CSO treatment sludges investigated varied significantly with biological sludges having the highest values.

   b. The calculated heat requirements for the incineration of the dewatered CSO sludges showed that a significant amount of auxiliary heat would be required to sustain combustion.

SECTION II

RECOMMENDATIONS

1. The treatment processes of thickening followed by centrifugation should be further utilized on a full scale basis to demonstrate the effectiveness of this treatment combination for the handling and disposal of CSO sludges.

2. Develop basic design criteria and operating characteristics of the thickening-centrifugation dewatering system in a form that can be translated into actual practice with minimum delay.

3. Develop capital and operating costs for the demonstrated treatment system.

4. Evaluate, on a nationwide basis, the extent of the wet-weather flow sludge problem with respect to quantities generated, characteristics and facility and cost requirements for handling and disposal of the CSO sludges.

5. Evaluate the "shock load" effect of CSO treatment residuals on dry-weather treatment plant operation and performance.

6. Evaluate alternative methods for ultimate disposal of raw CSO sludges and treated CSO sludges.

7. Investigate the feasibility of land treatment/disposal of raw CSO.

SECTION III

INTRODUCTION

The pollutional contribution of combined sewer overflows is of national importance. The magnitude of the problem is illustrated by the fact that more than 1,300 United States communities serving 25.8 million people have combined sewer systems (1). Sufficient information has been accumulated to confirm that the combined sewer overflow problem is of major importance and is growing worse with increasing urbanization, economic expansion, and water demands (2). Various methods for dealing with combined sewer overflows have been proposed. These methods pertain to the segregation of sewers, enlargement of interceptors and storage and treatment of combined sewer overflows. Among the various treatment methods are the physical, physical-chemical and biological treatment systems. Many of these concepts have been demonstrated or are planned for demonstration by the USEPA (3,4,5). As with most wastewater treatment processes, treatment of combined sewer overflows by the above processes results in residuals, which contain, in the concentrated form, objectionable contaminants present in the raw combined sewer overflows.

Sludge handling and disposal of the residual sludges from combined sewer overflow treatment has been generally neglected, thus far, in favor of the problems associated with the treatment of the combined sewer overflow itself. Optimum handling and disposal of these residuals must be considered an integral part of CSO treatment because it significantly affects the efficiency and cost of the total waste treatment system. Surprisingly, there is little information available in the literature concerning the characteristics, methods of disposal and economics of the sludge and its dispensation. EPA has recognized the need for defining the problems and establishing treatment procedures for handling and disposing of residual sludges from combined sewer overflow treatment. During 1973, USEPA awarded a contract (No. 68-03-0242) to Envirex Inc. to investigate Phase I (Characterization) of a two phase program whose total project objectives for both Phase I and Phase II are:

1. Characterize the residual sludges arising from the treatment (physical, physical-chemical, and biological) of combined sewer overflows (Phase I).

2. Develop and demonstrate a process treatment system for handling and disposing of the sludges arising from treatment of combined sewer overflows (Phase II).

3. Develop capital and operating costs for the treatment systems developed and demonstrated (Phase II).

This report incorporates the results of the characterization and feasibility investigations undertaken in Phase I of the above mentioned project.

The first and most difficult step in the ultimate disposal of sludge is the removal of the water normally associated with the sludges. In general, the less water associated with the sludge solids, the less costly the subsequent steps of ultimate disposal. The various steps leading to the ultimate disposal of the sludges arising from conventional dry-weather treatment are: 1) thickening by sedimentation or flotation, 2) digestion of thickened sludges, 3) dewatering by centrifugation or vacuum filtration and 4) ultimate disposal by incineration and/or landfill. Digestion of the sludge residuals is generally practiced after step one and the digested sludge may or may not be dewatered prior to ultimate disposal. Although information regarding the handling and disposal of sludges arising from combined sewer overflow treatment is lacking, it is indicated that the procedures used for handling conventional waste treatment sludges should be applicable. Therefore, the unit treatment processes of gravity thickening, flotation thickening, centrifugation, vacuum filtration and incineration were evaluated for the handling and disposal of CSO treatment residuals.

The specific objectives of this project were met through the performance of the following work tasks:

1. Desk top reviews evaluating a non-conventional method for handling combined sewer overflow residues by pumping back or bleeding back the residual sludges or stored overflows to the deriving sewerage system.

2. Field surveys conducted at selected EPA combined sewer overflow treatment sites to acquire and evaluate differences in sludge characteristics attributable to treatment process differences. In addition, bench scale investigations were conducted on residual sludges using conventional methods for handling combined sewer overflow residues.

3. Derivation, development, evaluation, and comparison of alternative process flow sheets for the handling and disposal of the sludges arising from the treatment of combined sewer overflows.

Several EPA demonstration projects were contacted for the procurement of the residual samples. Suitable samples were obtained from eight treatment sites in seven cities across the nation. A listing of the sites from which the samples were procured is shown in Table 1. Detailed descriptions of the dry and wet weather treatment facilities listed in Table 1 are presented in Appendix A. The ensuing sections of this report delineate the sampling procedures, test methods, treatability test results, desk top reviews, engineering evaluations and proposed recommendations.

Table 1. LIST OF CSO TREATMENT PROJECTS FROM WHICH SLUDGE SAMPLES WERE PROCURED

Location	Nature of process	Type of treatment	Sampling point
1. Humboldt Ave. Milwaukee, WI	Physical treatment	Storage/settling	Storage tank
2. Cottage Farm Cambridge, MA	Physical treatment	Storage/settling	Storage tank
3. Philadelphia, PA	Physical treatment	Microscreening	Screen backwash
4. Racine, WI	Physical/chemical treatment	Screening/dissolved-air flotation	Combined screen backwash & flotation scum
5. Hawley Road Milwaukee, WI	Physical/chemical treatment	Screening/dissolved-air flotation	Flotation scum
6. Baker Street San Francisco, CA	Physical/chemical treatment	Dissolved-air flotation	Flotation scum
7. Kenosha, WI	Biological treatment	Contact stabilization activated sludge	Stabilization tank
8. New Providence, NJ[a]	Biological treatment	Trickling filtration	Primary clarifier; secondary clarifier

a. Both wet-weather and dry-weather treatment sludge samples were procured.

SECTION IV

SAMPLING, TEST METHODS AND PROCEDURES

SAMPLE COLLECTION

As mentioned previously, sludge samples were collected from eight treatment sites in seven U.S. cities. All samples were collected manually. Only one sample was obtained from each site for characterization and testing. Each of these samples was composited manually from several grab samples collected during the operation of the treatment facility. Most of the feasibility tests were conducted on site except for two sites where samples had to be air freighted to Milwaukee because of scheduling difficulties. These arrangements generally necessitated a sludge aging period of 4 to 36 hours after which the feasibility tests could be started. Laboratory analyses requiring immediate attention, such as BOD_5 and coliforms, were undertaken immediately while samples were refrigerated for other less critical analyses. Separate special samples were also preserved immediately in glass bottles having teflon lined stoppers for pesticides and PCB analyses.

Every effort was made to utilize uniform sampling and testing procedures for various sludge samples; yet certain special handling procedures had to be adopted for individual sludge samples because of their inherent differences. The following details the individual sample collections for the various sites visited.

1. Humboldt Avenue, Milwaukee, WI - This detention-chlorination treatment facility produces the entire contents of the storage basin as the treatment residuals. During overflow periods, the tank contents are mixed with only one of the seven rotary mixers to dispense chlorine and to enable the detention tank to act as a settling basin. After the overflow has subsided, all mixers are activated to resuspend settled solids and the pumpback of the tank contents to the sewer commences. Thus, large volumes of relatively dilute residuals are produced that must be disposed of in a satisfactory manner. A 0.9 cu m (240 gal.) sample of the resuspended contents of the storage tank was collected for the storm event of March 3, 1974.

   It was observed that the collected waste settled very poorly and the supernatant was very turbid. This may have been due to the fact that the tank contents were mixed overnight and any floc present was sheared. The suspended solids concentration of this sample was only 181 mg/l and further concentration of the solids present via sedimentation was deemed necessary prior to undertaking any thickening tests. To facilitate faster settling the waste was treated with 25 mg/l of ferric chloride and flocculated for two minutes. The waste was then allowed to settle for one hour before the supernatant was removed. Approximately two gallons of settled sludge was collected from the original sample. This chemically clarified and settled sludge was utilized in the bench testing and laboratory analyses.

2. Cottage Farm, Cambridge, MA - This detention-chlorination facility produces large volumes of retained residuals which are normally returned to the dry-weather treatment facility. No mixing provisions are available in the detention tank. This necessitates manual hosing down of the residual solids from the bottom of the tank after the supernatant has been pumped out. Two separate samples of this residual sludge were collected on February 20 and March 21, 1974.

3. Philadelphia, PA - This pilot scale demonstration facility utilizes microscreening treatment of combined sewer overflows. No suitable sludge sample could be collected during the contract period. However, a backwash waste sample was obtained manually by flushing Callowhill Street between Edgemore and 6th Streets with fire hydrant water on two occasions (January 30 and 31, 1974). Also, a small backwash sample from an earlier overflow (January 27, 1974) was collected. Comparison of the manually flushed and actual storm samples indicated that there were significant differences in their characteristics. Therefore, it was felt that any results derived from the thickening testing of the collected sample would not truly represent the sludges from microscreening treatment of CSO. Hence any results obtained from bench tests at this site were omitted from this report.

4. Racine, WI - The sludge at this site is generated by a screening/dissolved-air flotation system. Because of the nature of this system, two sludges are generated. The first of these is the backwash from the screening process. The second sludge is the scum produced from the dissolved-air flotation process. At this site residual solids from both sources are piped to a common tank and eventually returned to the sewer when sufficiently low flows are experienced. Since it was not physically possible to obtain separate representative samples of the screen backwash and floated scum at this site (due to the closed pipes carrying the two residuals), a 0.15 cu m (40 gal.) sample of the combined residuals was obtained from the holding tank. Due to the dilute nature of this sample it was deemed necessary to provide further concentration of the solids present via sedimentation prior to undertaking any thickening tests. The collected sample showed good amenability to settling and the residual solids could be concentrated to approximately 12% of the original volume within 30 minutes of sedimentation. However, this reduced volume of recovered sludge was not sufficient to conduct all bench-thickening tests. Therefore, another larger sample was collected from the holding tank from the next storm event during September 1973. To facilitate collection of a large concentrated sample, the combined contents of the holding tank were allowed to settle in the same tank at the treatment site. A 0.08 cu m (20 gal.) sample of the concentrated sludge having a solids content of 2.72% was then drawn off for thickening tests.

5. Hawley Road, Milwaukee, WI - This site also has a screening/dissolved-air flotation pilot demonstration system with a treatment capacity of 18,925 cu m/day (5 mgd). During the storm event of July 21, 1973, only the dissolved-air flotation scum was obtained since the screen backwash system did not require activation. Several grab samples collected manually during the operation of the treatment facility were manually composited to one 0.15 cu m (40 gal.) sample for characterization and thickening tests.

6. Baker Street, San Francisco, CA - The dissolved-air flotation process is used for the treatment of CSO at this site. Flexibility exists to permit recycling of either the treated effluent or raw influent stream for air saturation under pressure. The chemical feed systems are provided for adding alum, polyelectrolyte, caustic and sodium hypochlorite solutions. A 0.15 cu m (40 gal.) grab sample of the floated scum was obtained on February 12, 1974 for characterization and laboratory thickening tests. The treatment facility was operated in the effluent recycle mode of operation using alum, caustic and polyelectrolyte during this storm event.

7. Kenosha, WI - A biological type treatment system using the contact stabilization process (modified conventional activated sludge process) is utilized at this site for the treatment of CSO. The system is designed to treat 75,700 cu m/day (20 mgd) of combined sewer overflow. The clarification and solids handling facilities are shared with the dry-weather treatment plant to obtain optimum use of the equipment. During dry-weather, waste activated sludge is discharged through the stabilization tank to maintain a supply of viable stabilized sludge ready for use at all times. During an overflow, this stabilized sludge is mixed with the raw waste and aerated in the contact tank for a period of 15-30 minutes after which the solids are settled in a final clarifier and returned to the stabilization tank. During a storm event, all solids removed from the raw waste or biologically produced are retained within the system, i.e. in the contact tank, stabilization tank or clarifier.

A 0.15 cu m (40 gal.) sludge sample was obtained from the aerated stabilization tank immediately after the overflow stopped on August 9, 1973. This point of sampling represented the most practical sampling point for obtaining a representative sample of the residual waste solids.

8. New Providence, NJ - This facility is designed for the treatment of domestic wastewater with a high amount of stormwater infiltrate during wet-weather periods. However, because of the biological nature of the treatment system (trickling filtration), the biota is kept alive by continuous operation during dry-weather periods. Due to the dual use of this trickling filter facility, two sludge samples were collected, one during dry-weather and one during wet-weather. Samples of the final clarifier and primary clarifier sludge were collected during both the dry and wet-weather periods.

The primary sludge was sampled from the sludge discharge line from the primary clarifier. About 0.13 cu m (35 gal.) was collected for the dry-weather sample and about 0.08 cu m (20 gal.) was collected for the wet-weather sample. The final clarifier sample was withdrawn from the end of the sludge line, where it mixes with the flow at the head end of the plant. About 0.13 cu m (35 gal.) was collected during the dry-weather period for on-site tests while about 0.08 cu m (20 gal.) was collected during the wet weather event for characterization and bench tests.

ANALYTICAL PROCEDURES

Analytical procedures were conducted in accordace with Standard Methods for the Examination of Water and Wastewater (6) and EPA's Methods for Chemical Analysis of Water and Wastes (7). Details are presented in Appendix B.

SLUDGE THICKENING BENCH TEST PROCEDURES

The bench tests consisted of gravity thickening, dissolved-air flotation thickening, centrifuge dewatering, and vacuum filtration. Appendix B contains detailed descriptions of the sludge thickening bench scale testing procedures. A brief description of these tests is presented below:

1. Gravity Thickening - These tests were conducted in one liter graduated cylinders. The cylinders were filled with sludge to the 1000 ml mark and allowed to settle for at least one hour. During this time readings of the position of the interface were taken and recorded along with the elapsed time. This test was then repeated using a variety of sludge concentrations. Following these tests, various flocculating chemicals were screened to determine the optimum chemical and dosage for floc formation. The chemical was then added to the sludge at the predetermined dosage and another set of settling tests were conducted to define the effects of chemical flocculation. The data derived was then analyzed by a combination of the Coe and Clevenger (8) and Mancini (9) methods to define design parameters for a gravity thickener.

2. Dissolved-Air Flotation Thickening - The basic equipment used in these tests was a graduated cylinder, stopwatch, and pressurized flow source. To conduct the test a predetermined amount of sludge was placed in the graduated cylinder and pressurized flow was introduced into the sludge until the total volume reached 1000 ml. The position of the interface was then recorded along with the time of the reading. This test was conducted with different amounts of sludge so that the optimum recycle rate could be determined. Once determined, a series of tests were conducted to determine the optimum chemical dosage. The test yielding the best estimated scum concentration and rate of rise was then selected.

3. Centrifuge Dewatering - Chemically untreated and/or treated sludge was centrifuged for various times at different "G" (gravitational) forces. The resultant centrate was decanted off, measured, and analyzed for suspended solids. The sludge depth was then measured and penetrability was determined via a glass rod. From the data recorded, cake solids, cake quantity, and optimum spin time and speed were determined.

4. Vacuum Filtration - Aliquots of the sludge with different chemical dosages were filtered through a Whatman filter paper held in a Buchner funnel. The volume of the filtrate and the elapsed time were recorded as the test progressed. The specific cake resistance was then calculated to determine the optimum chemical dosage. The filter paper was replaced with filter cloth. A variety of cloths were screened to determine which cloth would best discharge the cake. This cloth was then applied to the filter leaf and placed in approximately two liters of chemically treated sludge for a specified pickup time. The leaf was rotated out of the sludge and held upside down for the specified drying time. The filtrate was then volumetrically measured and both the filtrate and cake were analyzed for solids. The data was then tabulated to determine the optimum conditions for vacuum filtration.

SECTION V

CHARACTERIZATION OF CSO SLUDGES

The characterization of CSO sludges is presented according to the following groupings based on the type of treatment process utilized at the various sites.

A. Physical Treatment and/or Storage/Settling

1. Milwaukee, WI (storage/settling)
2. Cambridge, MA (storage/settling)
3. Philadelphia, PA (microscreening)

B. Physical/Chemical Treatment

1. Racine, WI (screening/dissolved-air flotation)
2. Milwaukee, WI (screening/dissolved-air flotation)
3. San Francisco, CA (dissolved-air flotation)

C. Biological Treatment

1. Kenosha, WI (contact stabilization)
2. New Providence, NJ (trickling filtration)

A discussion of the volumes produced and the sludge characteristics emanating from these groups is presented in the following sections. The sludge quantity and quality data are based on the laboratory analyses of one grab or manual composite sample from each site. The analyses were performed on the raw samples prior to the conduct of the sludge treatment feasibility tests.

SLUDGE VOLUMES

The sludge volumes produced per storm event at each site and the estimated volumes of sludge that would result from the treatment of the entire combined sewer area for the respective cities are presented in Table 2. The volumes shown represent average values and were derived from the past data obtained at these sites. Estimates of the average residual sludge volumes produced per unit of raw combined sewer overflow treated are also shown in this table for the various treatment types investigated. Comparative available sludge volume data for high rate filtration treatment of CSO are also included from the Cleveland, OH study (10).

Table 2. SLUDGE VOLUMES PRODUCED PER STORM EVENT FOR VARIOUS CSO TREATMENT METHODS

Site	Type of Treatment	Contributing areas, 00 Ac: To Site	Contributing areas, 00 Ac: Entire combined sewer	Contributing areas, 00 Ac: Entire city drainage	Average volume of raw CSO treated per storm[a] 000 gal.	Average residual sludge volume per storm[a] 000 gal.		Volume of residual sludge requiring thickening: volume of raw CSO treated %	Projected sludge residual volumes /storm event for entire CSO area 000 gal.		Solids content of the residual sludge %	
Humboldt Ave., Milw. WI	Storage/settl'g	5.7	172.8	1500	3900	3900	(34.7)[c]	0.9	118,150	(1050)[c]	0.015	(1.74)[c]
Cambridge, MA	Storage/settl'g	333.3	364.7	2610	8800	1500	(18.0)[c]	0.2	1,640	(19.5)[c]	0.016	(4.4)[c]
Philadelphia, PA	Microscreening	0.11	1600	2286	82.6	3.5		4.2	50,600		0 70	
Racine, WI	Screening/ flotation	4.7	7.0	1145	2530	121[d]		4.8	181		0.84[d]	
Hawley Road, Milw. WI	Screening/ flotation	4.9	172.8	1500	204.6	1.45[e]		0.7	1,278		3.65[e]	
San Francisco, CA	Dissolved-Air flotation	1.68	300	300	303.0	1.82		0.6	325		2.25	
Kenosha, WI	Contact stabilization	12.0	13.3	92.2	3500	122.6		3.5	236.5[h]		0.83	
New Providence, NJ	Trickling filtration	24.3	b	24.3								
Primary - WW[i]					3060	194.2		6.8[g]	210.2		0.12	
Secondary - WW[i]						16.0[f]					2.50	
Primary - DW					900	18.0[f]		4.9[g]	44.2		0.38	
Secondary-DW						26.2[f]					0.46	
Cleveland, OH	High Rate filtration		440	620	10	0.4		4.0			0.01 to 1.0	

a. Based on past data from various sites.
b. There are no contributing storm sewers. The system treats sanitary sewage with excessive storm water infiltrate.
c. Reduced volume of concentrated solids achieved by settling of solids in the holding tank. It is assumed that only settled solids will require further handling and thickening and the supernatant can be discharged to the receiving water.
d. Floated scum plus screen backwash water.
e. Floated scum only.
f. Sludge production in gallons produced per day.
g. Combined residuals from primary and secondary clarifiers
h. During an average run only 57.5% of CSO from contributing areas is treated by the wet-weather demonstration system
i. WW = wet-weather; DW = dry-weather

Ac = 0.405 ha; gal. = 0.003785 cu m

As seen in Table 2, the volumes of residual sludges produced from the treatment of CSO vary from 0.2 percent to 6.8 percent of the raw flow treated. Among the various types of CSO treatment residuals evaluated during this study, the storage/settling treatment produced the least amounts of residuals as a percentage of raw CSO flow treated for further thickening when it is assumed that the settled supernatant is discharged to the receiving water. Sludge volumes produced by dissolved-air flotation treatment alone were less than 1% of the raw CSO treated (San Francisco and Hawley Road, Milwaukee), however, the addition of screen backwash water to the flotation sludges increased the residual volume to 4.8% of the raw CSO flow (Racine). The solids content of the flotation sludges dropped from approximately 3% to 0.8% due to the dilution by screen backwash water. Thus, when screening is used with dissolved-air flotation, the screen backwash water can account for nearly 80% or more of the sludge volume. Therefore, it is indicated that any possible sludge handling method for the CSO sludge should include separation of the screen backwash water and the floated sludge. Since the backwash is generally low in solids, it could possibly be bled back to the sewer and treated with the raw flow at the dry-weather treatment facilities, if such added hydraulic and solids loadings can be accommodated. Sludge handling would then be concerned with less than 20% of the volume that is due to the floated sludge, which is about 2-4% solids. This sludge could be thickened by gravity settling or flotation and then further concentrated by centrifugation or vacuum filtration before final disposal.

Because comprehensive rainfall monitoring was conducted as part of the Racine project (11), the sludge production can also be related to the rainfall amounts. It was found that an average rainfall amount of 0.25 cm (0.10 in.) must fall in the combined sewer area before overflow will begin. After overflow does begin, each additional 0.25 cm (0.10 in.) of rainfall will produce an average overflow of 17,922 cu m (4,735,000 gal.) for the subject area having a composite average coefficient of runoff (c) value of 0.65. Using 0.048 cu m (12.7 gal.) of sludge produced per unit volume of CSO treated reveals that every 0.25 cm (0.1 in.) of rainfall after the first 0.25 cm (0.1 in.) will produce 957 cu m (226,000 gal.) of CSO sludge for the Racine study area.

Among the biological types of CSO treatment processes investigated, the contact stabilization at Kenosha, WI produced 3.5% of the raw CSO treated through the system as the residual sludge volume. This percentage was calculated from the data obtained from the Kenosha stormwater project report (12). The report showed that during an average run, 13,248 cu m (3.5 million gal.) of CSO was treated removing 3,977 kg (8,760 lbs) of suspended solids and produced another 663 kg (1,460 lbs) of solids. Using these numbers and an average solids concentration of 1% (the solids concentration of one grab sample obtained during this study was 8,300 mg/l), the residual sludge volume was calculated to be 464 cu m (122,600 gal.) or 3.5% of the raw CSO. Comparatively, the average sludge volume from the dry-weather plant operation at Kenosha is indicated to be approximately 1.1% of the average raw flow treated through the plant (13). (This percentage includes both the primary as well as the waste activated sludge.) On a mass basis, it is indicated that an average of 15,193 kg (33,500 lbs) of solids are produced per day from the primary and secondary facilities. The average dry-weather flow through the plant during this period (1974-75) was 83,280 cu m/day (22 mgd). Using these numbers, the amount of residual solids produced from 13,248 cu m (3.5 million gal.) of dry-weather flow would be 2417 kg (5329 lbs) of solids. Thus, it is indicated that the residual solids produced during dry-weather treatment are approximately 52% of the solids produced during wet-weather treatment at Kenosha, WI. The lower production of solids during dry-weather treatment is expected because of the weaker solids concentration of the influent waste during dry-weather flow. Average influent suspended solids concentration during dry-weather flow varied between 125 and 160 mg/l during 1970 to 1975 compared to a weighted mean average of 332 mg/l during 1972 for the wet-weather treatment.

The residual sludge volume from the primary and secondary clarifiers was calculated to be 6.8% of the raw CSO from the trickling filtration treatment at New Providence, NJ (14,15). The comparative dry-weather residual sludge was estimated to be 4.6% of the influent flow and was again found to be less than the wet-weather sludge production.

In order to compare the sludge volume production from various types of CSO treatment, some data was made available to this study from another EPA pilot demonstration project (10) in which high-rate deep-bed filtration was utilized for the treatment of CSO. It was indicated that an average of 4.0% of raw CSO was produced as residual sludge (backwash wastewater) from this type of treatment. The solids content of this wastewater varied from approximately 10,000 mg/l after 1-2 minutes of backwashing to less than 100 mg/l after approximately 5 minutes of backwashing.

SLUDGE CHARACTERISTICS

The characteristics of the CSO sludges obtained from this study are presented in Tables 3-5. The solids content of the sludge samples varied widely. The holding tanks produced sludges of 1.7%, 4.4% and 11.0% solids after sedimentation; the screening up to 0.7%, dissolved-air flotation 2.25% (San Francisco) and 3.65% (Hawley Road, Milwaukee), screening/dissolved-air flotation 0.84% (Racine), and biological treatment 0.12 to 2.5% for trickling filtration (New Providence) and 0.83% for contact stabilization (Kenosha).

The volatile fraction of the sludge suspended solids varied from 25% to 63%. Biological treatment sludges showed the highest volatile fraction, about 60%, while physical and physical/chemical treatment sludges showed only a 25% to 48% volatile fraction.

The BOD, TOC, DOC (dissolved organic carbon), total phosphorus and TKN (total Kjeldahl nitrogen) concentrations also varied widely. The highest concentrations were found in the sludge sample obtained from Cambridge, MA.

The soluble nitorgen forms, ammonia, nitrites, and nitrates, were low in concentration for all sites except the New Providence secondary sludge which was very high in ammonia concentration.

It may be noted that the suspended solids value for Cambridge, MA shown in Table 3 at 11% solids is significantly higher than the corresponding value

Table 3. CHARACTERISTICS OF CSO SLUDGES FROM PHYSICAL OR STORAGE/SETTLING TYPE TREATMENT

Parameter	Units	Sites Milwaukee[a]	Cambridge[a]	Philadelphia
Total Solids	mg/l	18,900	126,900	8,660
Suspended Solids	mg/l	17,400	110,000	7,000
Total Volatile Solids	mg/l	9,150	57,500	2,520
Volatile Suspended Solids	mg/l	8,425	41,400	1,755
BOD_5	mg/l	2,200	12,000	--
TOC	mg/l	7,250	16,200	1,032
Dissolved Organic Carbon	mg/l	55	949	--
Total Phosphorus (as P)	mg/l	109.1	293.4	11.5
Total Kjeldahl Nitrogen (as N)	mg/l	56	28	46
Ammonia (as N)	mg/l	4.1	3.2	--
NO_2 (as N)	mg/l	0.15	0.4	--
NO_3 (as N)	mg/l	1.7	0.5	--
Density	gm/cm^3	1.015	1.06	1.05
pH	--	6.4	5.7	7.4
Total Coliforms	#/100 ml	--	210,000,000	--
Fecal Coliforms	#/100 ml	--	2,800,000	--
Fuel Value	cal/gm (BTU/lb)	--	2721 (4903)	1971 (3227)
PCB's	µg/kg. dry	47	6,570	ND
pp' DDD	µg/kg. dry	ND	ND	ND
pp' DDT	µg/kg. dry	ND	170	ND
Dieldrin	µg/kg. dry	20	58	ND
Zinc	mg/kg. dry	799	946	1,189
Lead	mg/kg. dry	2,063	1,261	2,448
Copper	mg/kg. dry	201	757	200
Nickel	mg/kg. dry	159	126	289
Chromium	mg/kg. dry	243	260	52
Mercury	mg/kg. dry	2.7	0.01	2.1

ND = None detected.
a = After settling of holding tank contents.

Table 4. CHARACTERISTICS OF CSO SLUDGES FROM PHYSICAL/CHEMICAL TYPE TREATMENT

Parameter	Units	Sites Racine	 Milwaukee [a]	 San Francisco [a]
Total Solids	mg/l	9,769	42,700	24,000
Suspended Solids	mg/l	8,433	41,900	22,500
Total Volatile Solids	mg/l	3,596	11,350	9,400
Volatile Suspended Solids	mg/l	3,340	10,570	8,850
BOD_5	mg/l	1,100	3,200	1,000
TOC	mg/l	260	6,050	1,600
Dissolved Organic Carbon	mg/l	60	340	67
Total Phosphorus (as P)	mg/l	39.2	149	166
Total Kjeldahl Nitrogen (as N)	mg/l	112	517	375
Ammonia (as N)	mg/l	6.3	12.5	7.5
NO_2 (as N)	mg/l	<0.1	<0.1	0.02
NO_3 (as N)	mg/l	<0.1	<0.1	0.1
Density	gm/cm^3	1.01	1.07	1.014
pH	--	6.9	7.2	5.2
Total Coliforms	#/100 ml	40,000	6,400,000	6,300,000
Fecal Coliforms	#/100 ml	1,400	220,000	17,000
Fuel Value	cal/gm (BTU/lb)	1,961 (3534)	1,359 (2449)	1,950 (3514)
PCB's	μg/kg. dry	603	775	113
pp' DDD	μg/kg. dry	ND	225	29
pp' DDT	μg/kg. dry	ND	TR	96
Dieldrin	μg/kg. dry	24	9	192
Zinc	mg/kg. dry	1,638	855	768
Lead	mg/kg. dry	1,023	164	1,583
Copper	mg/kg. dry	481	248	367
Nickel	mg/kg. dry	215	173	<83
Chromium	mg/kg. dry	215	150	1,667
Mercury	mg/kg. dry	2.3	2.1	3.9

ND = None Detected TR = Trace (<0.2 μg/l on wet basis)
[a] = Floated sludge only

Table 5. CHARACTERISTICS OF CSL SLUDGES FROM BIOLOGICAL TREATMENT

Parameter	Units	Kenosha	New Providence Wet-Weather Sludges Primary	New Providence Wet-Weather Sludges Secondary
Total Solids	mg/l	8,527	2,010	25,500
Suspended Solids	mg/l	8,300	1,215	25,070
Total Volatile Solids	mg/l	5,003	1,120	15,500
Volatile Suspended Solids	mg/l	5,225	780	14,770
BOD_5	mg/l	1,700	728	11,200
TOC	mg/l	3,400	700	13,000
Dissolved Organic Carbon	mg/l	29	220	710
Total Phosphorus (as P)	mg/l	194	22	436
Total Kjeldahl Nitrogen (as N)	mg/l	492	65	6
Ammonia (as N)	mg/l	24	9	180
NO_2 (as N)	mg/l	0.055	0.02	0.02
NO_3 (as N)	mg/l	0.065	0.11	0.09
Density	gm/cm^3	--	1.005	1.013
pH	--	7.9	6.9	--
Total Coliforms	#/100 ml	1,200,000	44,000,000	1,300,000,000
Fecal Coliforms	#/100 ml	79,000	3,400,000	1,000,000
Fuel Value	cal./gm. (BTU/lb)	3,446 (6210)	3,585 (6460)	3,583 (6457)
PCB's	µg/kg. dry	767	547	--
pp' DDD	µg/kg. dry	93	ND	--
pp' DDT	µg/kg. dry	TR	ND	--
Dieldrin	µg/kg. dry	88	ND	--
Zinc	mg/kg. dry	7,154	697	1,294
Lead	mg/kg. dry	528	<498	353
Copper	mg/kg. dry	1,454	995	1,020
Nickel	mg/kg. dry	528	995	784
Chromium	mg/kg. dry	1,278	746	2,471
Mercury	mg/kg. dry	2.6	100.5	--

TR = Trace (<0.2 µg/l on wet basis)

Table 5. (continued)
CHARACTERISTICS OF CSO SLUDGES
FROM BIOLOGICAL TREATMENT

Parameter	Units	New Providence Dry-Weather Sludges Primary	New Providence Dry-Weather Sludges Secondary
Total Solids	mg/l	4,168	4,930
Suspended Solids	mg/l	3,840	4,620
Total Volatile Solids	mg/l	3,205	3,638
Volatile Suspended Solids	mg/l	3,200	3,610
BOD_5	mg/l	1,600	2,950
TOC	mg/l	--	--
Dissolved Organic Carbon	mg/l	92	54
Total Phosphorus (as P)	mg/l	40.7	92.7
Total Kjeldahl Nitrogen (as N)	mg/l	214	277
Ammonia (as N)	mg/l	38	25
NO_2 (as N)	mg/l	<0.01	0.019
NO_3 (as N)	mg/l	0.03	0.01
Density	gm/cm^3	1.006	1.005
pH	--	6.7	6.7
Total Coliforms	#/100 ml	20,000,000	8,500,000
Fecal Coliforms	#/100 ml	2,000,000	1,000,000
Fuel Value	cal./gm. (BTU/lb)	4,452 (8022)	--
PCB's	µg/kg. dry	ND	--
pp' DDD	µg/kg. dry	1,750	--
pp' DDT	µg/kg. dry	878	--
Dieldrin	µg/kg. dry	3,000	--
Zinc	mg/kg. dry	1,288	1,744
Lead	mg/kg. dry	240	304
Copper	mg/kg. dry	600	953
Nickel	mg/kg. dry	480	913
Chromium	mg/kg. dry	847	2,049
Mercury	mg/kg. dry	6.2	21.5

for the same site in Table 2 at 4.4%. These two values represent two separate grab samples. The first sample showed a solids value of 4.4%, however, enough sample was not available for detailed analysis. Therefore, a second sample in larger volume was obtained from this site. This sample was analyzed for various constituents and was found to have the significantly higher solids concentration. The lower value was used in Table 2 comparisons because it was judged to be more representative of the residual solids concentrations based on communications with the plant personnel (15).

The sludge densities ranged from 1.005 to 1.0 gm/cm^3 for the various sludges analyzed with an average value of 1.026 gm/cm^3. The storage/settling type sludges had density values of 1.015 gm/cm^3 and 1.06 gm/cm^3 for Milwaukee and Cambridge sites. The physical/chemical treatment sludges had densities ranging between 1.01 to 1.07 gm/cm^3.

The pH of the sludge samples collected ranged from 5.2 to 7.9. The low value of 5.2 was found in San Francisco where alum was being used.

As would be expected with higher volatile solids, the biological sludges also had the greatest fuel values among the sludges evaluated. The biological sludges had an average fuel value of 3,515 cal/gm (6334 BTU/lb) while the other sludges produced an average fuel value of 2,032 cal/gm (3662 BTU/lb). It can also be noted that the fuel value for the primary and secondary sludges for dry as well as wet-weather treatment at New Providence, NJ were quite close, ranging between 3500 to 4500 cal/gm (6307 to 8109 BTU/lb).

As can be seen in Table 5, the various constituents such as suspended solids, volatile suspended solids, BOD_5 and TOC showed significantly higher concentrations in the secondary wet-weather sludge compared to the dry-weather sludge for New Providence. This increase in wet-weather solids may be attributed in some part to the synthesis of dissolved organic matter present in the sewer infiltrate resulting in higher solids from the secondary clarifier. The weaker suspended solids in the primary wet-weather sludge may be a result of the dilution of the influent sewage solids by the infiltrate.

The results of the PCB and pesticide analyses are summarized in Table 6. Among the PCB's and pesticides analyzed for the various sludges, the PCB's were generally of the highest concentrations. The Cambridge sludge showed the highest concentrations of PCB's and pp'DDT while the Milwaukee (Hawley Road) sludge had the highest concentration of pp'DDD and the San Francisco sludge had the highest concentration of dieldrin. The significantly higher PCB value at Cambridge may have been a result of pollutant buildup in combined sewers and incomplete flushing of the tank residuals at the end of previous storm events.

Table 6. AVERAGE PCB AND PESTICIDE CONCENTRATIONS IN CSO SLUDGES

Parameter	Average (µg/kg dry)	Range	Site of highest concentration
PCB	407[a]	ND-6570	Cambridge
pp'DDD	43	ND-225	Milwaukee
pp'DDT	44	ND-170	Cambridge
Dieldrin	49	ND-192	San Francisco

a. Represents the average PCB value without Cambridge data. When Cambridge PCB value is used, the average PCB value becomes 1347 µg/kg dry solids, which is significantly higher than all other sludge sample values.

ND = none detected.

The heavy metals concentrations analyzed for various sludges are summarized in Table 7. Zinc was usually found to be the heavy metal of the highest concentration with the concentration of lead also being high. The secondary wet-weather sludge from New Providence and the sludge from Kenosha were both found to be high in heavy metal concentration. At New Providence, increased heavy metal loadings may be a result of the leaching of these metals in the groundwater infiltrate. Comparing the average heavy metal values obtained during this study for wet-weather sludges with the 33 dry-weather plant sludge average (17), it is seen that the dry-weather values are significantly higher than the wet-weather values. The higher heavy metal values in dry-weather sludges may be a result of accumulations of these pollutants in sludge blankets over a longer period compared to shorter wet-weather treatment durations.

Table 7. AVERAGE HEAVY METAL CONCENTRATIONS IN CSO SLUDGES

Parameter	(mg/kg dry)	Range	Site of highest concentration	Average 33 dry-weather plant sludges[b], mg/kg dry
Zinc	1,700	697-7154	Kenosha	4,210
Lead	1,100	164-2448	Philadelphia	2,750
Copper	636	200-1454	Kenosha	1,590
Nickel	372	83- 995	New Providence	680
Chromium	787	52-2471	New Providence	1,860
Mercury	2.2	0.01-100.5	New Providence	10

a. Represents average mercury concentration without New Providence data. When this data is used, the average mercury value becomes 14.5 mg/kg dry solids.

b. See Reference 17.

SECTION VI

BENCH-SCALE THICKENING TESTS AND EVALUATIONS

The results of the bench-scale dewatering tests on the sludge samples procured from the various CSO treatment facilities mentioned earlier are discussed for each site in the three subsections below. Along with the technical feasibility evaluations, economic analyses of the dewatering techniques were also developed for each site. A complete listing of the cost data and the assumptions made to develop these data are presented in Appendix C. Cost data represent the latest available, December, 1974 prices for capital equipment and updated published cost data (18,19) to December 1974 prices. Since the CSO treatment systems at Philadelphia, Milwaukee, (Hawley Road), and San Francisco were pilot scale studies and did not treat the entire overflow from the sewer outfall drainage area, these sites were scaled up to the entire flow for the respective technical and economic evaluations that follow.

A. PHYSICAL TREATMENT AND/OR STORAGE/SETTLING

Three samples of the treatment residuals were obtained under this category of CSO treatment. Two of these samples were procured from storage treatment sites in Milwaukee, WI, and Cambridge, MA. The third sample was the backwash waste from the pilot microscreening unit in Philadelphia, PA. The detained contents (CSO) from storage basins were very dilute compared to conventional sludges. For disposal, these residuals can either be pumped or bled back to the dry-weather sewage treatment facilities or dewatered on-site. A discussion of the pump/bleedback concept of such residuals is presented in Section VII of this report. For on-site treatment, it is imperative that such residuals be concentrated via conventional techniques prior to their thickening treatment. Therefore, for the sludge treatability studies herein, only the clarified sludge residuals were evaluated. As mentioned earlier, in Section IV, because of the special handling required for the procurement of these three sludge samples, only limited amounts of residuals were available for the dewatering tests. Accordingly, only gravity, flotation and centrifugation thickening tests were conducted on these samples.

<u>Milwaukee, WI, and Cambridge, MA</u>

Figures 1 and 2 show the treatment schematics of the bench-scale dewatering techniques investigated at Milwaukee and Cambridge, respectively. The Milwaukee CSO sample was first treated with 25 mg/l ferric chloride and

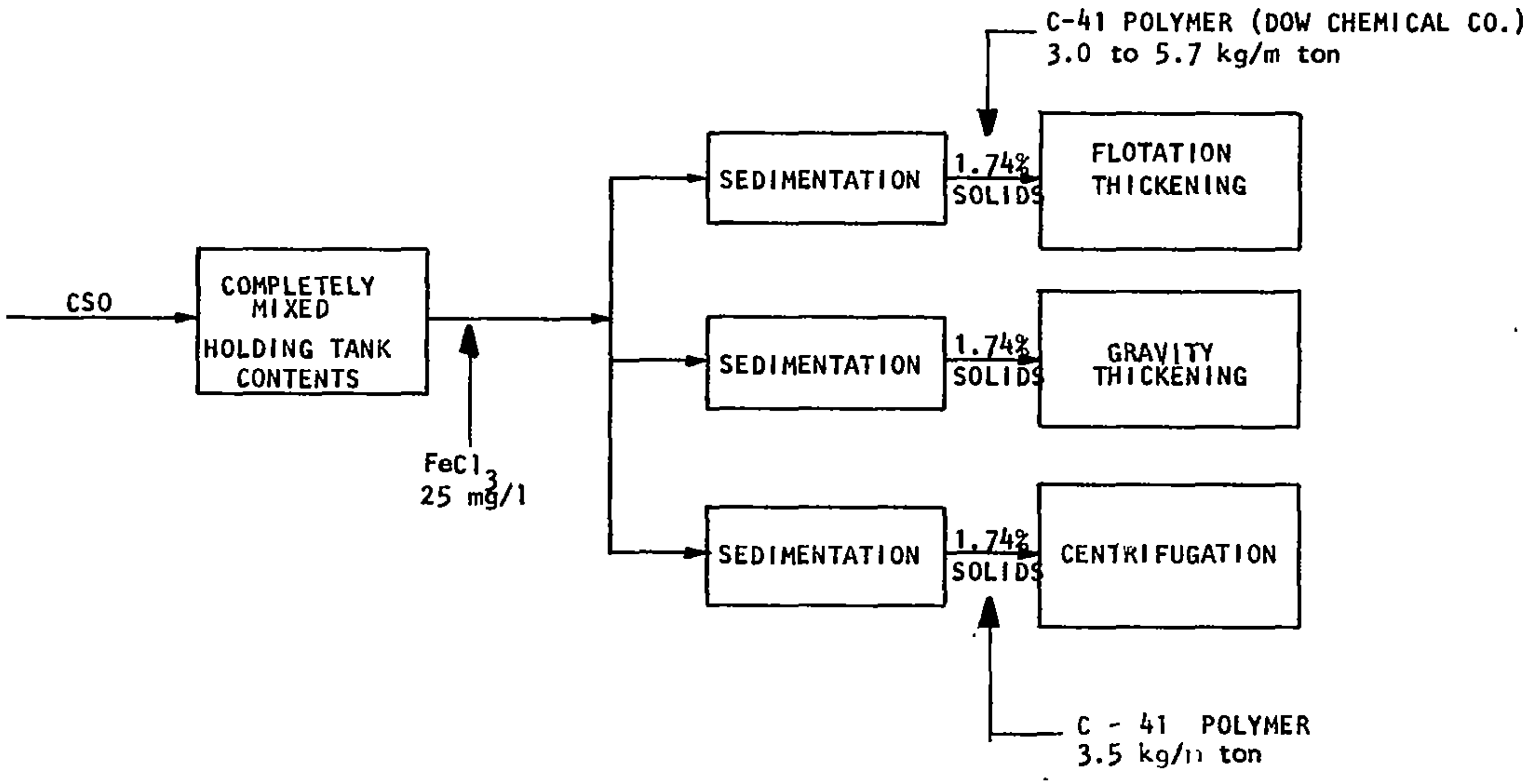

Figure I. Humboldt Avenue, Milwaukee, WI - bench scale dewatering tests

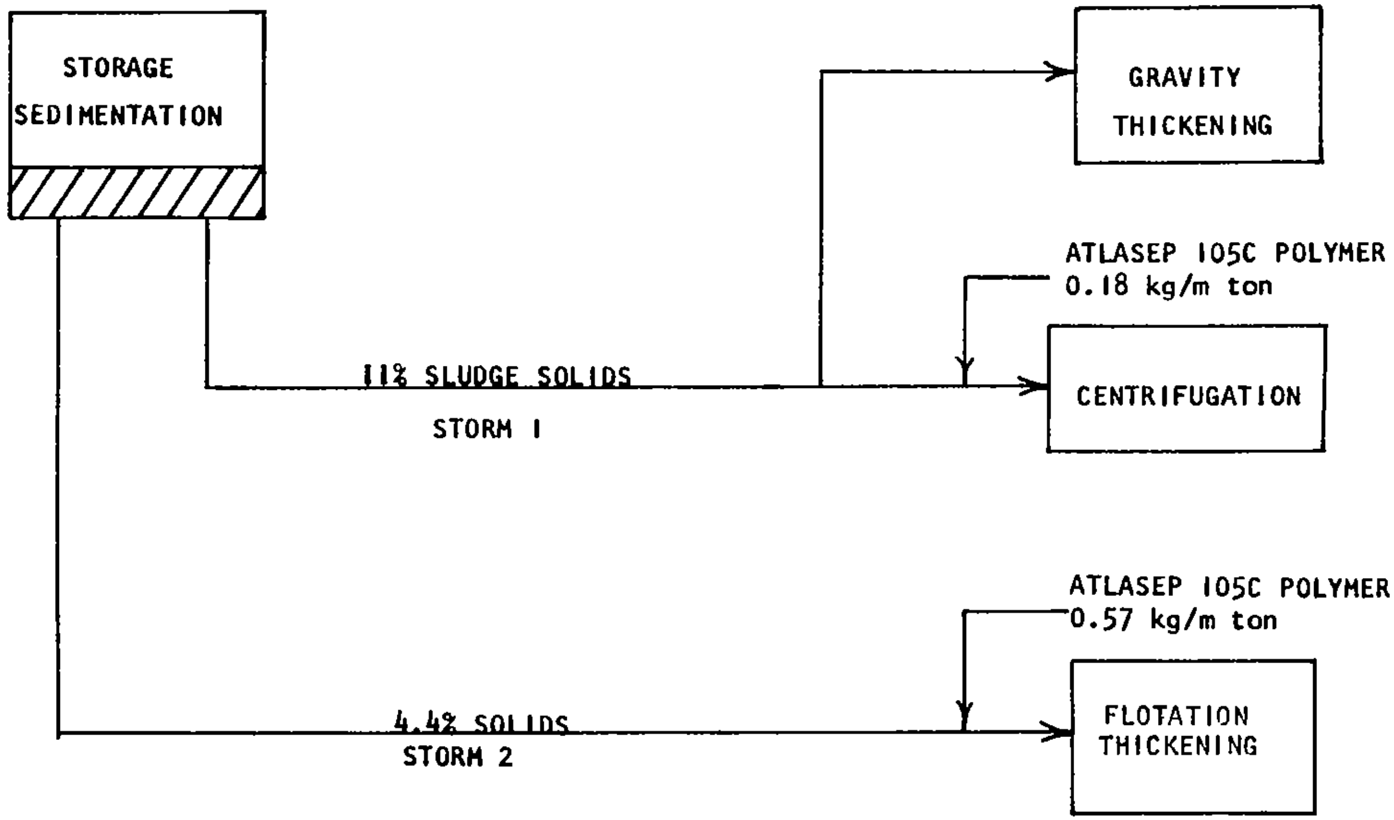

Figure 2. Cambridge, MA - Bench scale dewatering tests